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AN INTRODUCTION TO DIGITAL MODULATION AND OFDM TECHNIQUES

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Summary

This Report differs from most BBC Research Department Reports in that it does not contain details of a specific project undertaken at Kingswood Warren. While there has been a continuing development of aspects of digital modulation systems by BBC research engineers over many years, the purpose of this Report is to be tutorial. That is, digital transmission techniques need to be explained in a general way if full advantage is to be obtained from other Reports concerning digital broadcasting transmission systems. There are, however, references to other specialised publications if particular details are required.

The text of this Report is based on a paper which was prepared for an Institution of Electrical Engineers' vacation school on new broadcast standards and systems. It discusses, at a general level, the various issues and trade-offs that must be considered in the design of a digital modulation system for broadcast use. It particularly concentrates on giving a simple description of the use and benefits of OFDM systems. The particular issues can be applied to various future broadcast systems which are under development at the BBC and as part of collaborative work in international projects.

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1. INTRODUCTION

Digital modulation systems are not new, but recent years have seen a rapid growth in the number and range of techniques which can be used to modulate digital information for transmission over an RF channel. In parallel with this has been the design and introduction of digital systems for broadcasting, for example NICAM 728, MAC/packet and RDS.

The current trend is to design complicated but flexible systems; these can be arranged to offer many additional features which may be of benefit to both the audience, broadcasters and equipment manufacturers. The whole approach is predicated on the assumption of very large scale integrated circuit technology and European or global markets for the receivers, thus making complicated circuits available at domestic prices. As a result, many of these systems are developed as part of pan-European projects which combine the expertise of broadcasters, transmitter and receiver manufacturers.

The result is that a wide range of techniques are, or have been, proposed for future digital broadcast systems and the technology to use these techniques can be made available in domestic receivers.

The purpose of this Report is to discuss, at a general level, the various issues and trade-offs which are considered in the design of digital modulation systems for terrestrial broadcast use. The Report will concentrate on describing the Orthogonal Frequency Division Multiplexing (OFDM) techniques which have been developed for Digital Audio Broadcasting (DAB) and may be used in a future Digital Television Broadcasting (DTB) system. The Report first discusses the basic principles of digital modulation and then moves on to consider some of the advanced techniques which are used.

Before considering digital modulation systems in detail two more general issues must be addressed; why use a digital system? Why modulate a signal?

Digital systems are proposed and promoted for many reasons. However, the main technical reasons for using a digital system are:

- Increased spectrum and/or power efficiency can be obtained in many cases using digital systems.
- Digital information can be recovered after many stages of processing and transmission and the baseband signal reconstructed without any additional degradation.
- The modulation systems can be designed to be more resistant to channel and equipment imperfections.
- Additional data information services, in addition to the main broadcast programme, are possible.
- Flexibility in the number and quality of programmes can be achieved.

The purpose of modulation is to allow information to be conveyed over a channel, in this case an RF channel. Fig. 1 *(overleaf)* shows (in general terms) the components which are required. There are many types of digital modulation system, and the choice for any application is affected by requirements of that application for:

- Spectrum efficiency.
- Resistance to channel distortions (e.g. multipath).
- Tolerance of transmitter and receiver imperfections.
- Maximisation of signal coverage or minimisation of transmitted power levels.
- Minimisation of interference protection requirements.

However, as will become apparent, many of these requirements conflict. Therefore the optimum modulation system for each application can only be found by carefully balancing the relative priorities of each requirement. In addition, there is usually considerable interaction between the design of the digital modulation system and the channel and source coding, as greater sophistication in one area can change the requirements of the other components, or allow them to be made simpler. This last point is a very important one.

2. SIMPLE SYSTEMS

2.1 Basic digital modulation methods

There are many ways of modulating digital information onto a carrier; but these can be divided into three generic types — amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift

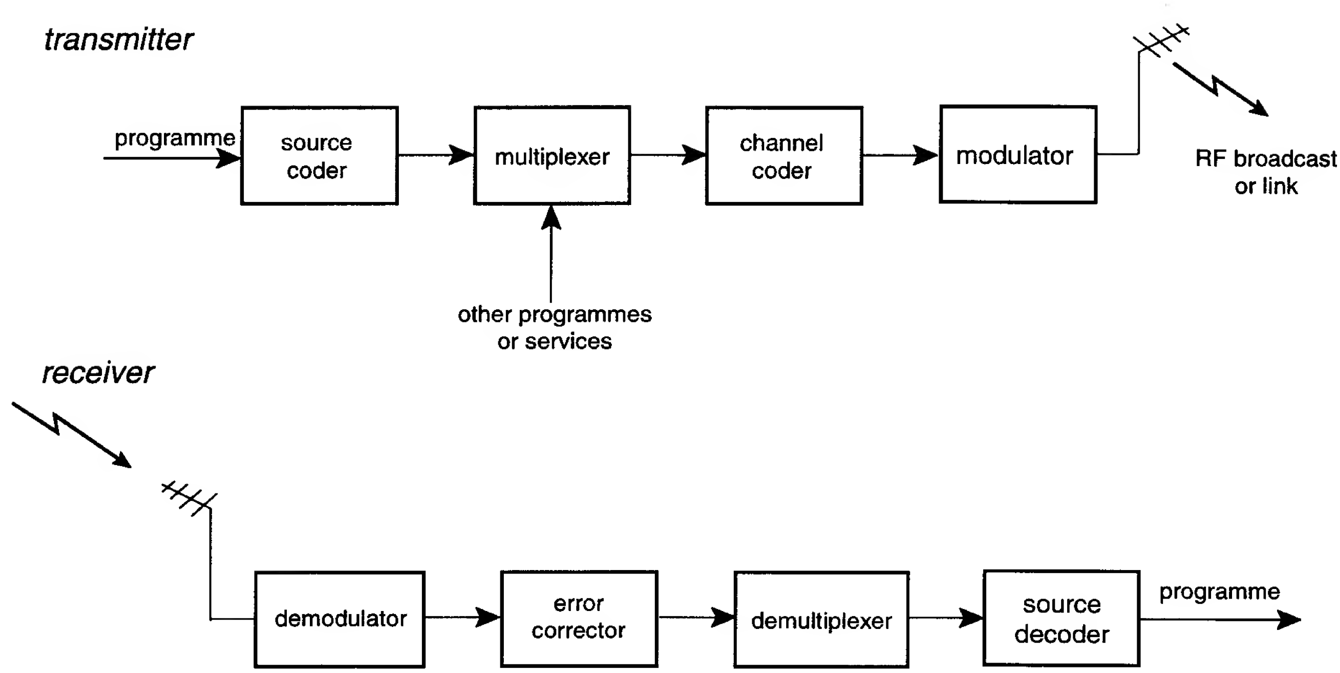


Fig. 1 - Generalised digital transmission system.

keying (PSK)[1]. However, the most current systems use a mixture of amplitude and phase shift keying with data being transmitted on both the in-phase (I) and quadrature (Q) components of the carrier. These systems are known as quadrature amplitude modulation (QAM) systems and further discussion in this Report will be limited to such systems.

Information is transmitted by choosing to transmit one phase and amplitude state, from a number of options, for a period of time known as a *symbol.* Modulation systems are best represented and described with reference to the phase constellation (the set of possible phase and amplitude states) used for each symbol, Fig. 2. The use of a modulation system with more phase states allows more data to be carried in each symbol.

2.2 Practical considerations

So far, transitions between phase states have been assumed to occur instantaneously, therefore the spectrum of the resulting signal has components at all frequencies. The exact spectrum shape is described by the Fourier transform of the pulse shape in the time domain — in this case rectangular. In most practical systems the bandwidth of the signal must be limited and so the ideal signal is filtered. Filtering changes the shape, in the time domain, of the received signal. If the filter parameters are chosen carefully, the performance of the demodulated signal is not degraded and the conventional data 'eye' is produced, Fig. 3. The optimum sampling point for the data symbol is in the most open part of the eye.

The modulation systems have been described as transmitting information by the choice of point in the phase constellation. However, an absolute phase reference is usually not available at the receiver and so the I and Q channels cannot be uniquely identified. One of two possible solutions are usually used; either a training sequence is transmitted to identify the I and Q channels, or the information is coded as the change in phase state from the previous symbol. The latter is known as differential coding[2].

2.3 The effect of impairments

Simplistically, the effect of noise in the channel is to produce uncertainty in the position of the points in the phase constellation. If the demodulator detects the phase state to be closest to the wrong point in the constellation, then a symbol error (and consequently one or more bit errors) occurs. The ruggedness of the signal is related to the distance between the points in the phase constellation. As the spectrum occupancy is proportional to the symbol rate, systems using more phase states are more spectrum efficient. However, in these systems the distance between phase states is smaller, and errors are caused at higher signal-to-noise ratios (S/N). There is a theoretical link between these factors which was first derived by Shannon. The theoretical performance of any system can be compared with the theoretically achievable limit, Fig. 4[3]; it should be noted that E_b/N_0 (which stands for energy per bit divided by the noise power spectral density) is often used as a measure of S/N, as it provides a common basis on which to compare the performance of different systems.

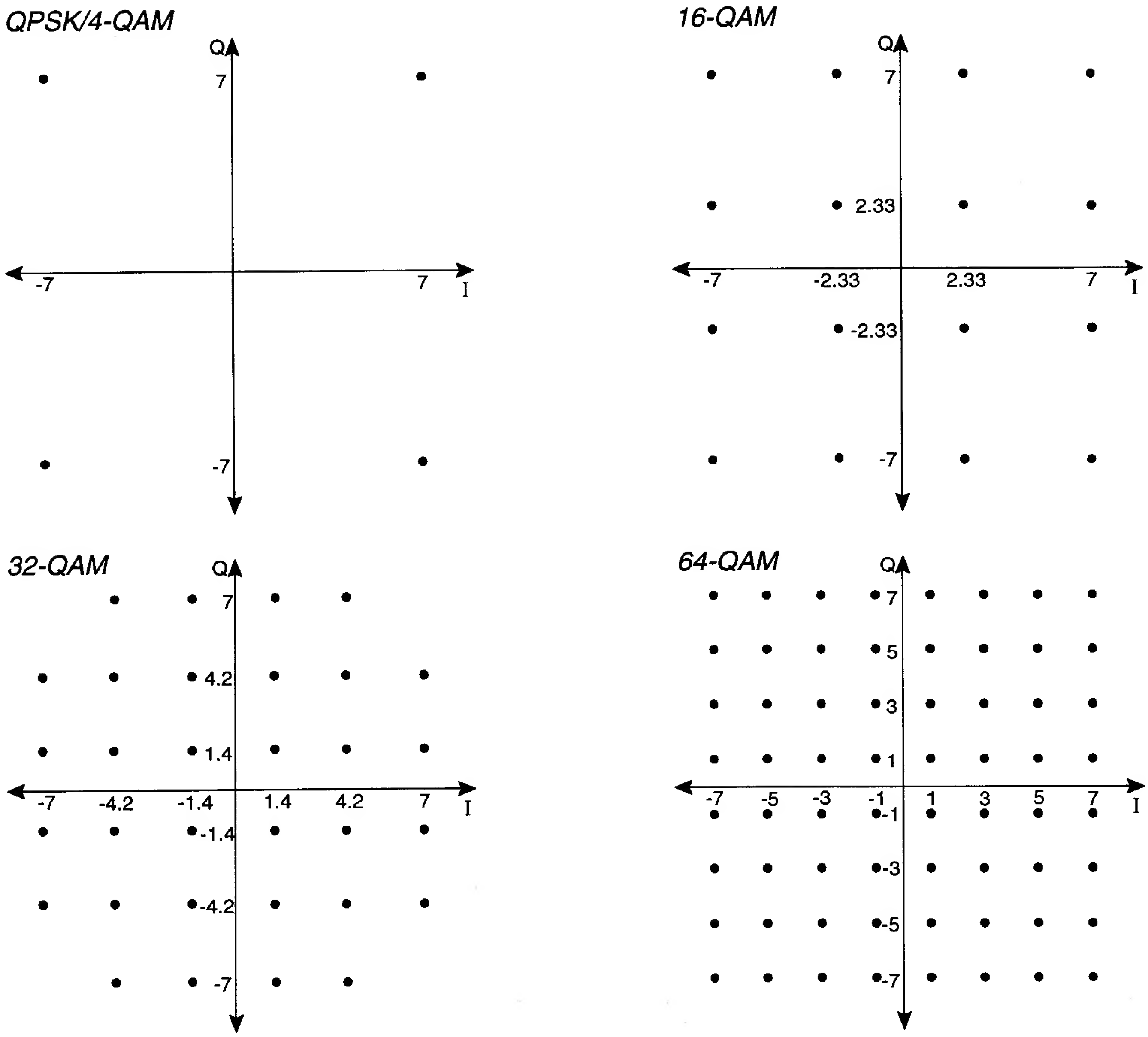


Fig. 2 - Phase constellations of example QAM digital modulation systems.

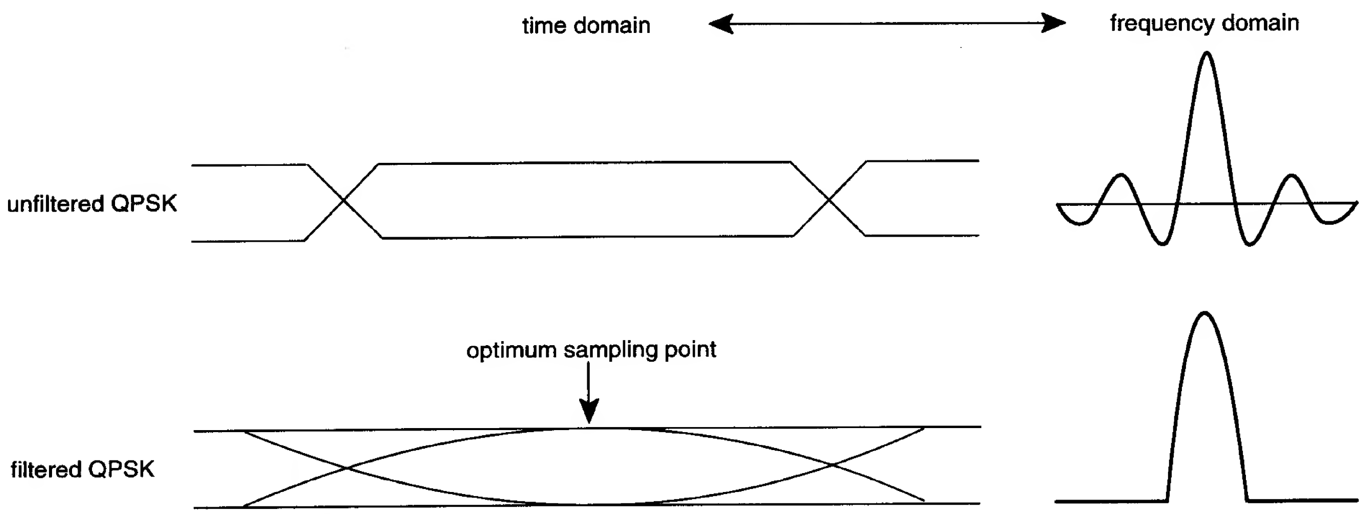


Fig. 3 - Rectangular and filtered QPSK signal representations in the time and frequency domains.

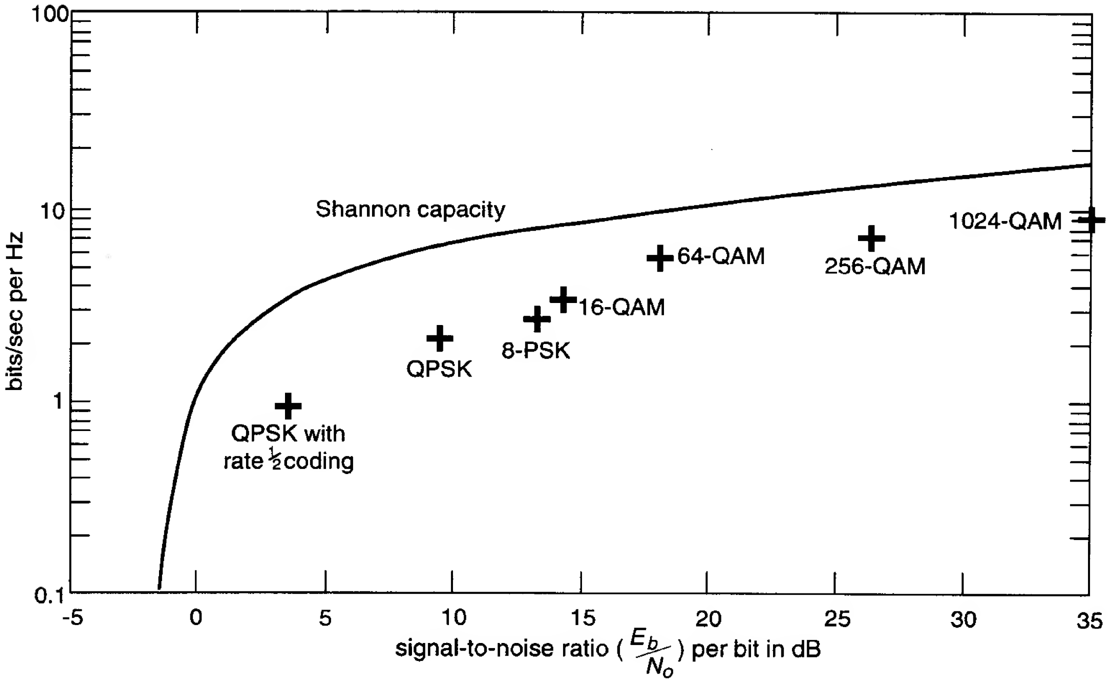


Fig. 4 - Comparison of modulation methods at 10^{-5} symbol error probability.

The effect of common types of interference in transmitting and receiving equipment is to change the shape of the spectrum and hence the shape of the data eye. This can result in a partial closure of the eye and hence a degradation in the system performance[4].

The major trade-offs between systems can now be understood. The spectrum width is determined largely by the symbol rate. Increased spectrum efficiency requires more bits of information and hence more phase states to be accommodated in each symbol. However, the more phase states there are, the closer the points in the constellation are spaced and so the less rugged the system.

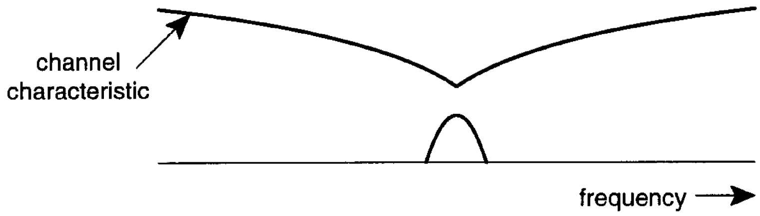
2.4 Problems with simple systems

There are several problems with simple digital modulation systems:

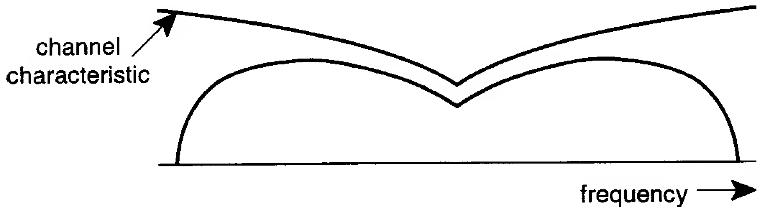
- They exhibit a relatively swift increase in number of errors as the signal level is reduced or interference levels increase. The theoretical performance in the presence of Gaussian noise is given by the complementary error function[5]. This is in contrast to analogue systems which degrade in performance relatively slowly as the signal level is reduced.
- They are degraded by multipath propagation[6]. In this case the same problem occurs with analogue systems.
- Unlike FM systems, most PSK systems exhibit large amplitude variations in the signal envelope. As a result, linear amplification is necessary to prevent re-generation of out-of-band frequency components.

Multipath propagation occurs when the demodulator receives many versions of the signal, each with slightly different time delays. If the delay is short compared with the symbol period, then the additional signal may add constructively (if the signals are in the same phase) or be destructive (if they are out of phase). The effect across the signal bandwidth will be the same — a flat fade. If the delay is longer than the symbol period then there is constructive and destructive interference at different frequencies across the signal bandwidth — a frequency selective fade. There will also be inter-symbol interference (ISI) in which components from two, unrelated symbols are presented simultaneously at the demodulator, Fig. 5.

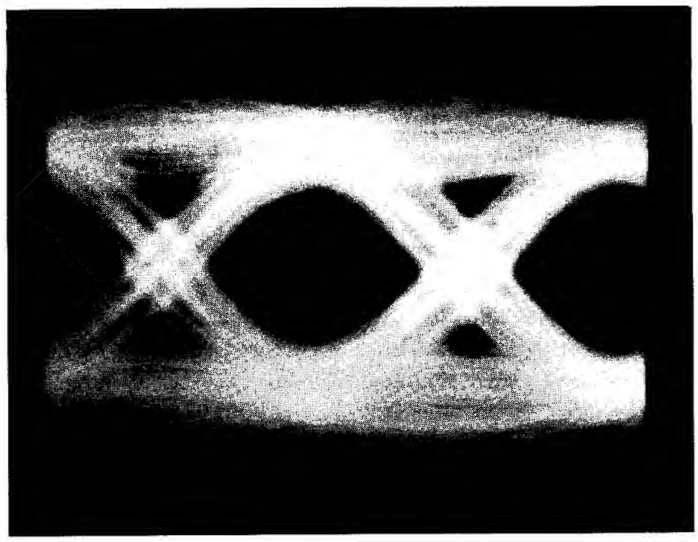
Both these problems are sometimes addressed by adding additional redundancy to the signal-channel coding. The data rate available to convey information is reduced but the ruggedness of the signal is improved. The effect of coding applied to a QPSK signal in a multipath channel[7] is shown in Fig. 6. Channel coding can be designed to match the characteristics of the channel or the source material. A key issue in system design is to achieve the optimum balance between these options. Coding designed to match the channel tends to produce the maximum improvement at low error rates and a very sharp failure characteristic. Coding designed to match the source material can be arranged to give a much more gradual failure characteristic.



(a) Signal suffering from flat fading.



(b) Signal suffering from frequency-selective fading.



(c) Resulting distortion of a data eye.

Fig. 5 - Effect on a signal of flat and frequency-selective fading.

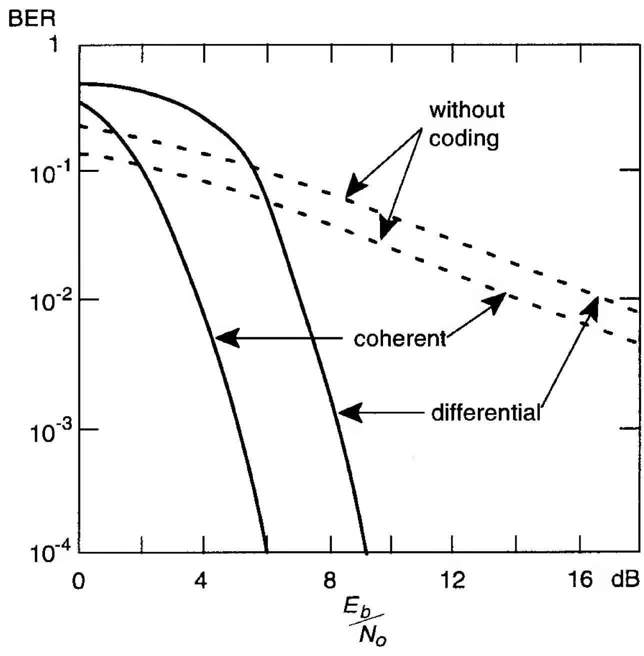


Fig. 6 - Effect of convolutional coding on a QPSK signal in a multipath channel.

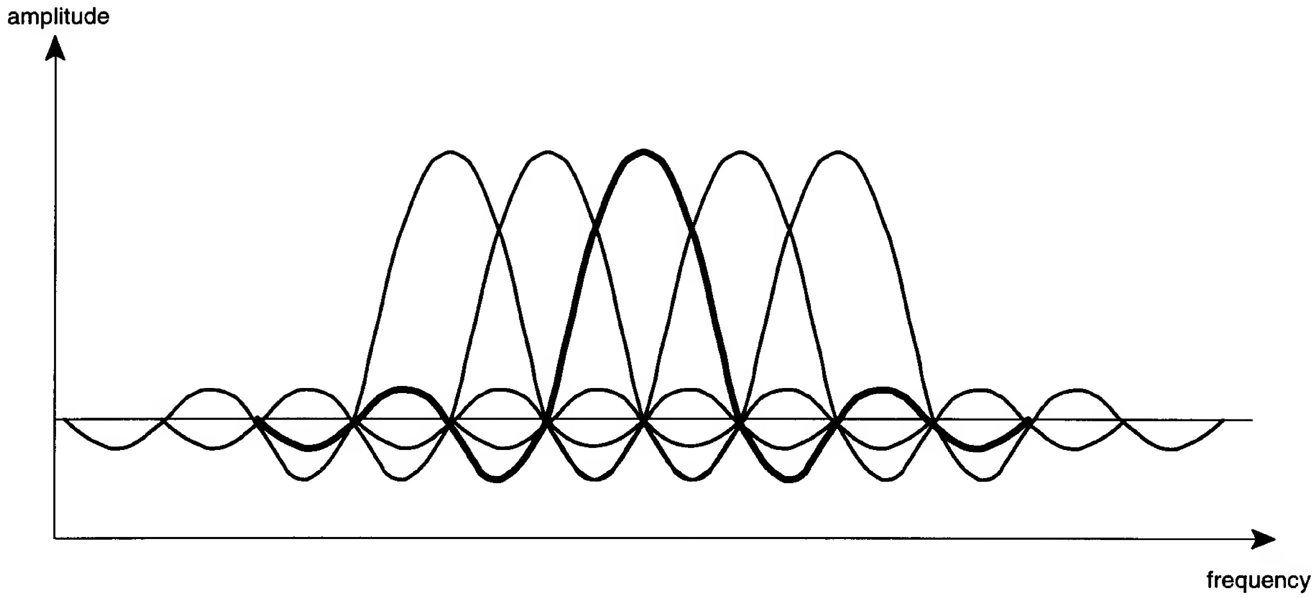


Fig. 7 - Carriers with orthogonal frequency spacing.

3. MORE ADVANCED MODULATION TECHNIQUES

Additional techniques have been developed to alleviate some of these problems. Examples are spread spectrum systems, orthogonal frequency division multiplex (OFDM) systems and adaptive equalisers. This Report will concentrate on OFDM systems which are being developed for next generation television and radio systems, as they provide additional benefits to rugged performance in the presence of multipath.

The premise of OFDM systems is that a rugged, multipath resistant modulation system is needed for relatively high-data rate signals. The high-data rate means that the spectral occupancy will be relatively wide. The presence of multipath means that frequency-selective fading is expected across this bandwidth.

The approach taken is to modulate the data onto a large number of carriers, each very closely spaced in frequency[7]. The symbol rate of each carrier is very low, giving it a narrow bandwidth. The envelope of the signal in the time domain is rectangular (i.e. they are unfiltered) giving them the conventional 'Sin x / x' spectrum shape., The key point is that the carriers are orthogonally spaced in frequency — that is, they are spaced such that there is no mutual interference, Fig. 7. The relationship is described mathematically in Fig. 8. The result is a rectangular signal spectrum, as the carriers are closely spaced giving an almost uniform power spectral density in-band and a very sharp reduction in power at the band edges, Fig. 9.

$$\int_{-\pi}^{\pi} \sin n\omega t \sin m\omega t \, d(\omega t) = 0, \ n \neq m$$
$$= \pi, \ n = m$$

Fig. 8 - Mathematical description of orthogonality.

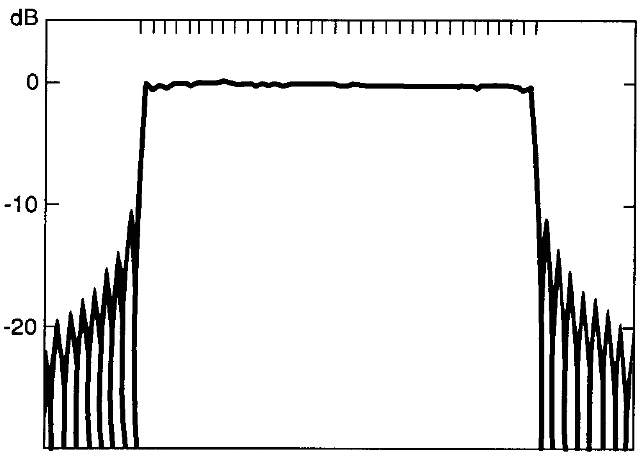


Fig. 9 - OFDM power spectrum.

The practical realisation of OFDM systems rests on the use of the digital implementation of a fast Fourier transform (FFT) to produce the large numbers of modulated carriers. A property of the FFT is that the frequency components are, by definition, orthogonal when integrated over the FFT period.

Benefit occurs when using this system in the presence of interference and multipath, as only *some* of the carriers will be affected at any one time. Fig. 10

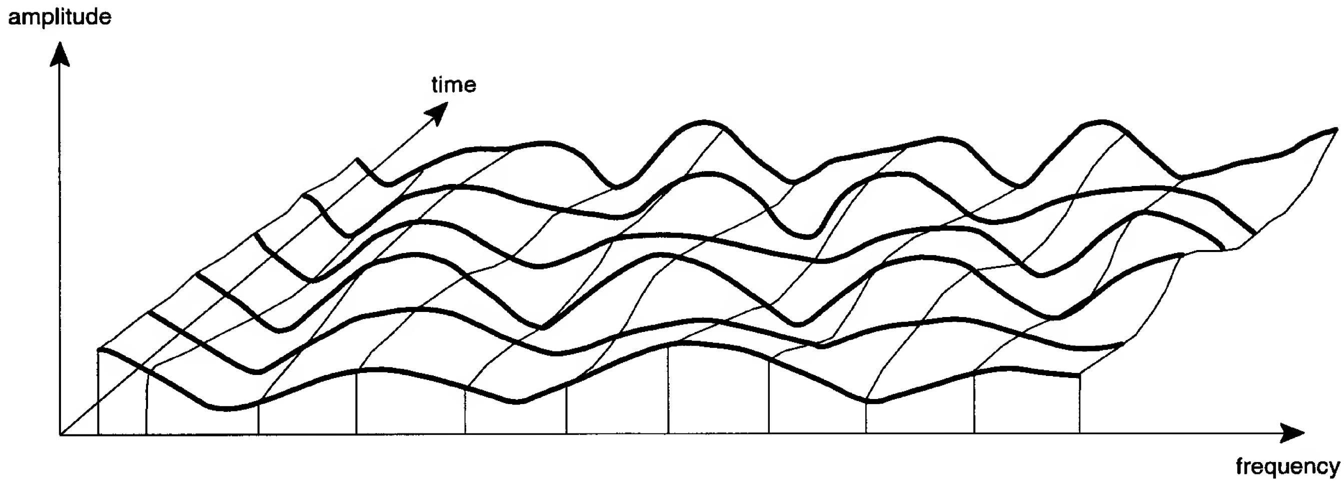


Fig. 10 - Multipath channel response.

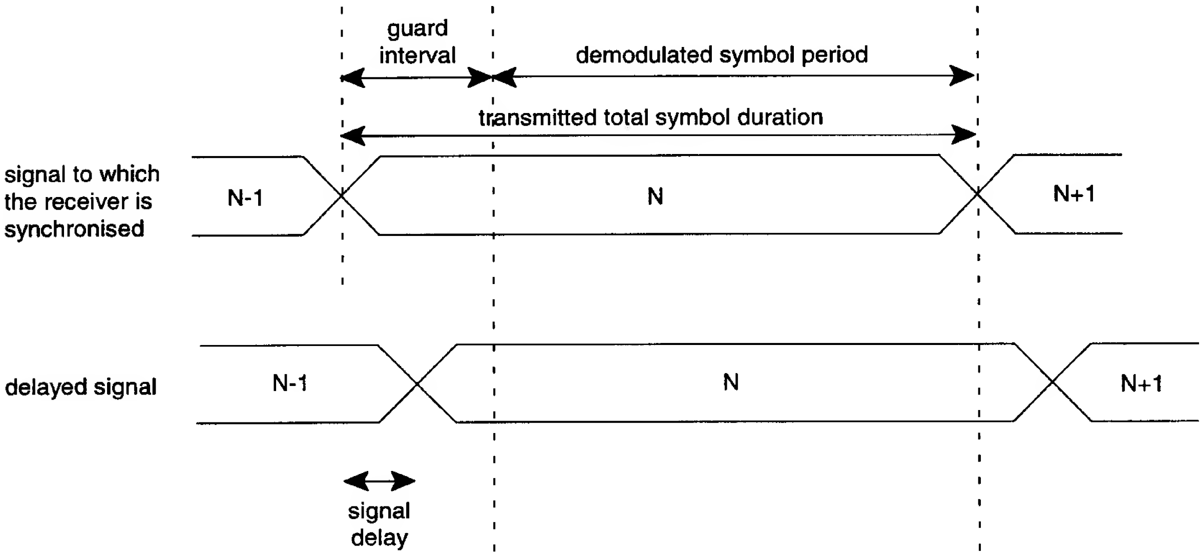


Fig. 11 - Multipath with a delay of less than the guard interval.

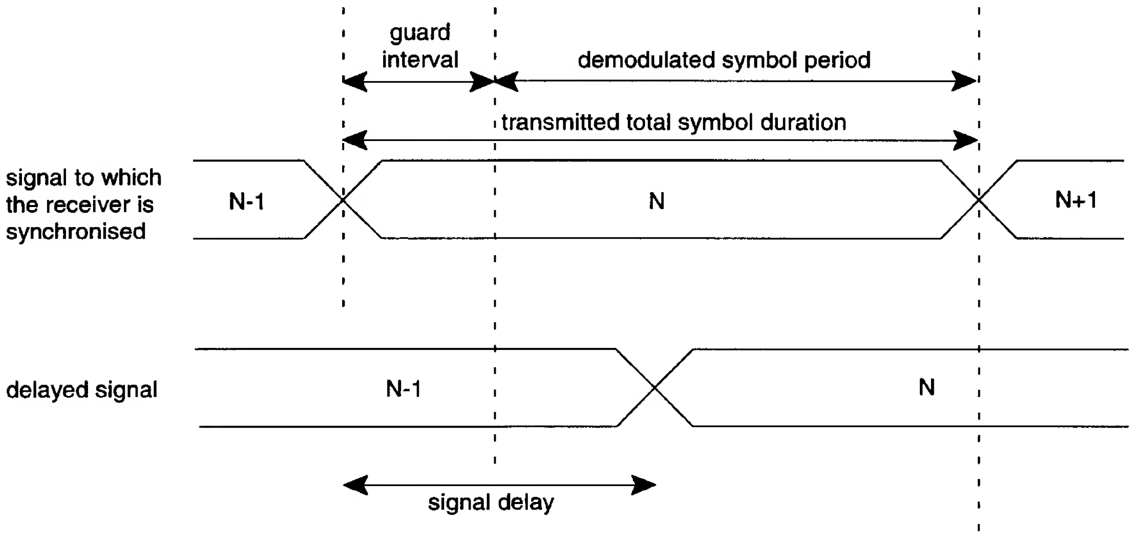


Fig. 12 - Multipath delay exceeding the guard interval.

shows an example channel response and the variation in level of signal component with frequency and time[8].

Three additional features can be added to improve performance:

- The data can be interleaved in time and frequency. That is, sequential data bits are transmitted separated in time and on different carriers[9]. The precise rule is given by an algorithm laid down in the system design. At the receiver, the effect of the loss of data from a carrier may be conditioned, as bursts of errors are broken up by the disinterleaving process.
- Redundancy in the form of channel coding permitting error correction can be added to correct errors arising from carriers which suffer from interference or multipath. Systems which use coding are termed Coded OFDM (COFDM) systems.
- The symbol period of data carried on each carrier can be increased to prevent multipath causing ISI. The additional time, known as the guard interval, not only prevents ISI but also allows the delayed signal power to be used constructively.

This last point can be seen most clearly by reference to Figs. 11 and 12 *(see previous page).* Fig. 11 shows a delayed signal with a delay of less than the guard interval. A part of the total signal power is taken and demodulated. It can be seen that this portion of both the signal components comprises only the wanted symbol and so no ISI occurs. However, Fig. 12 shows that when the signal delay exceeds the guard interval, part of the demodulated portion of the delayed signal comprises the wanted symbol and part of the next symbol. In this case, the delayed signal is partly helpful and partly interfering.

The result is a system with the same spectrum efficiency as the basic modulation system used on the individual carriers, but a greatly enhanced performance in the presence of interference and multipath. A representation of a COFDM signal with these features in the time and frequency domain is shown in Fig. 13.

A key benefit occurs when COFDM systems are used for wide-area broadcasting (in which the same service is broadcast from many transmitters). With conventional systems, interference is prevented by providing a number of frequency allocations. However with COFDM, the simultaneous reception of a signal from two transmitters appears at the receiver to be multipath propagation with a very long delay. COFDM systems can be designed to allow relatively long delayed echoes, and so all the transmitters in a network can be operated on the same frequency. The concept is known as a single frequency network (SFN)[10].

In planning SFN systems, the power in a delayed signal can be considered to be composed of a constructive and interfering component. The relative

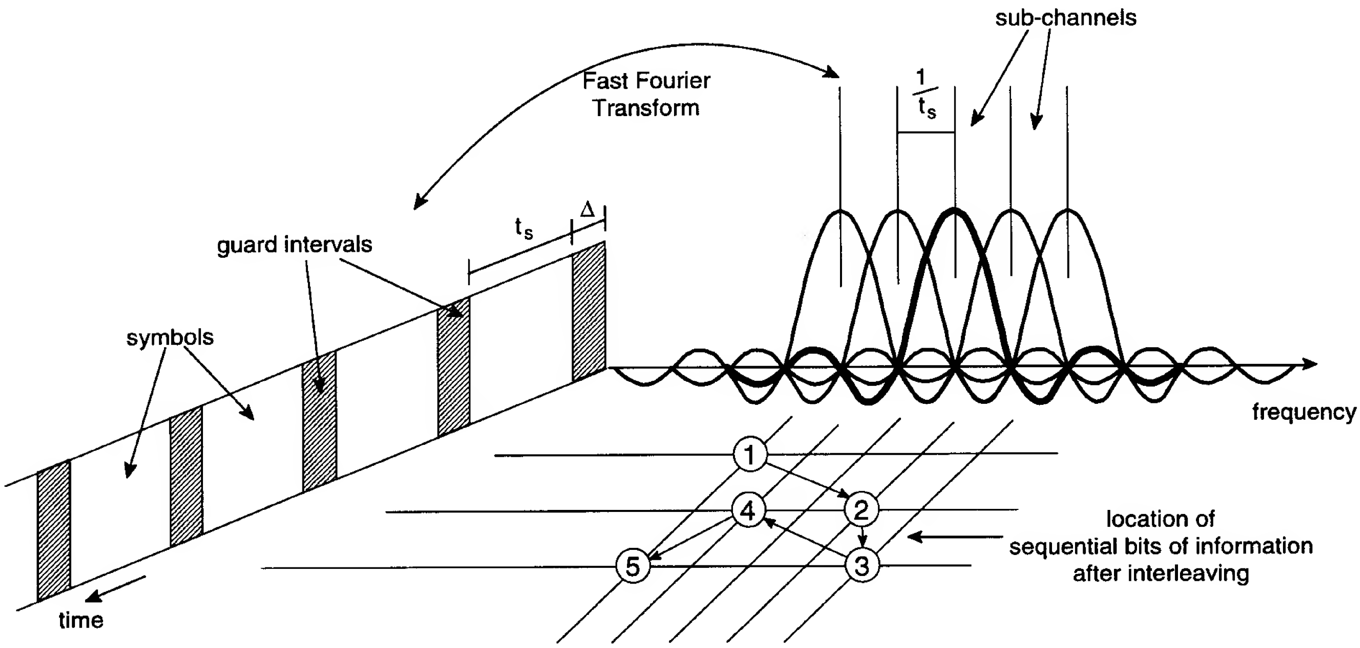


Fig. 13 - Spectral and temporal representation of a COFDM signal

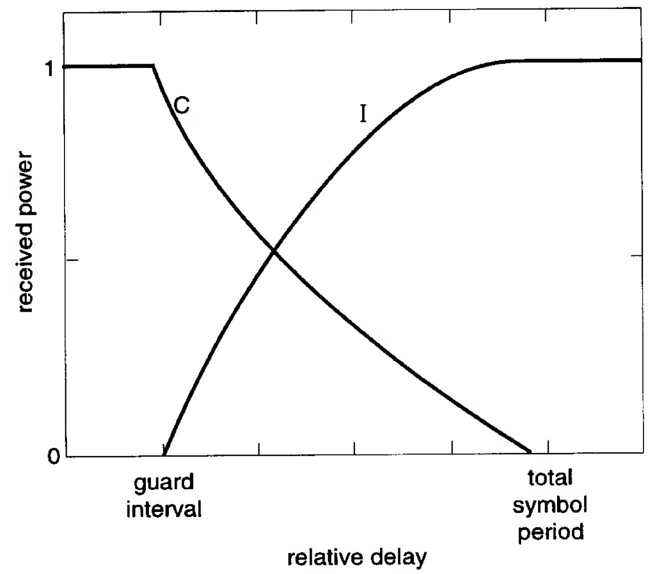


Fig. 14 - Proportions of delayed power which are constructive and interfering.

amounts of each component depend on the signal delay. The relationship is given in Fig. 14. For example, in the Eureka DAB System one operating mode provides a guard interval of 250 μs. This can allow an SFN with transmitter spacings in excess of 75 km before problems with interference occur.

4. FRAMING AND DATA ISSUES

The data is usually organised into frames to assist in demodulation and decoding. It is often necessary to add specific information symbols at the start of each frame to help synchronisation of the RF circuits. An example of the frame structure used in DAB is shown in Fig. 15. The null symbol is used to provide frame synchronisation. The symbol which follows is used to provide information for automatic frequency control (AFC) and as a phase reference for the following symbols. This is necessary, as DAB uses differential coding.

Modern broadcast services consist of a number of ancillary data signals as well as the main programme information. In an OFDM system, the arrangement of these ancillary services around the main programme, their relative ruggedness and consequent service area, are important issues in the design of channel coding and modulation systems. The problem is further complicated when the total data signal consists of a number of programme services, and some of the ancillary data is common and some related specifically to individual services — as is the case with DAB. Separate and relevant performance criteria have to be developed for each of the components of the total system, with their relative coverage areas and failure criteria controlled using appropriate amounts of channel coding.

Systems containing many programme services (such as DAB, which can accommodate up to six high-quality stereo audio signals in a 1.5 MHz bandwidth) also allow considerable flexibility in the way that the data capacity can be allocated. The arrangement of data is signalled directly to the receiver as multiplex information. This arrangement allows the number, type and data rate of services to be changed dynamically. The DAB system provides a good example of where such flexibility would be useful. Additional programmes could be introduced in times of national emergency (for example, the rolling news channel created during the Gulf War) or to accommodate seasonal or special events (for example, cricket test matches).

5. CONCLUSIONS

In summary, flexible, rugged spectrum efficient, digital coding and modulation systems are the way that new broadcast systems will deliver high-quality signals to the public. Such systems can be provided by combining conventional modulation methods with OFDM techniques which have been developed more recently.

6. REFERENCES

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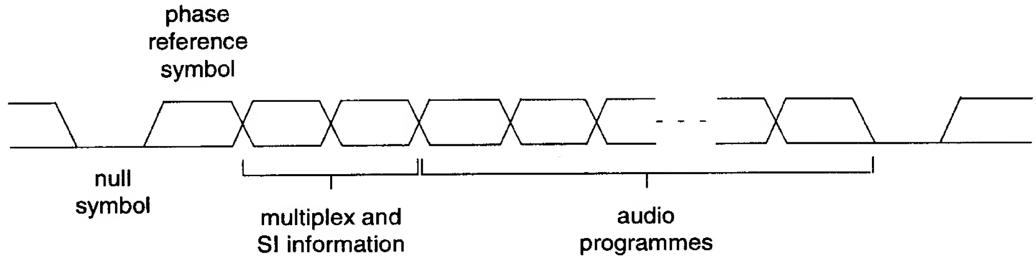

Fig. 15 - DAB frame structure.

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